Deceleration of projectiles in sand

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14. ABSTRACT

Penetration of projectiles was measured for hemispherical and conical nose shapes penetrating granular media. Targets were beds of Ottawa sand and Eglin sand. Projectiles were rigid metals. Experimental parameters that were varied included velocity (from 300 to 600 m/s), nose shape sand density, and scale (from 5 mm to 20 mm). Strong evidence for scale effects is found: 5 mm diameter projectiles are less effective penetrators than 12.5, 15, or 20 mm diameter penetrators.

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DECELERATION OF PROJECTILES IN SAND

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Abstract. Penetration of projectiles was measured for hemispherical and conical nose shapes penetrating granular media. Targets were beds of Ottawa sand and Eglin sand. Projectiles were rigid metals. Experimental parameters that were varied included velocity (from 300 to 600 m/s), nose shape, sand density, and scale (from 5 mm to 20 mm). Strong evidence for scale effects is found: 5 mm diameter projectiles are less effective penetrators than 12.5, 15, or 20 mm diameter penetrators.

Keywords: sand, penetration, Poncelet.
PACS: 45.40.Gj, 83.80Fg.

INTRODUCTION

Experiments on sand penetration with rigid projectiles were independently conducted by Keiko Watanabe at Osaka University (OU), William Cooper at the Air Force Research Laboratory (AFRL), and Stephan Bless with graduate student Bobby Peden at the Institute for Advanced Technology (IAT) at The University of Texas at Austin. In all cases the grain size was distributed around 0.5 mm. Each group used different projectiles; OU and AFRL used Eglin sand. At OU, steel flat-nose right-circular cylinders that were 14.9 mm diameter and 26 mm long were shot vertically into Eglin sand of density 1.51 to 1.56 g/cm^3. At AFRL, the projectiles were hemispherical-nose steel cylinders, 20 mm diameter by 127 mm long, shot horizontally. At IAT, Ottawa sand at 1.56 g/cm^3 was used. Projectiles were either steel or 17.6 g/cm^3 tungsten alloy or hemispherical-nose rods 5 mm diameter by 50 mm long, all fin-stabilized (for flight in air). More details about these experiments are provided in [1]. IAT also shot standard .50 M2 ball bullets on horizontal trajectories and measured deceleration into sand with a photonic Doppler velocimeter (PDV) (see, e.g., [2] for PDV description), although final penetration was not obtained in those experiments.

EXPERIMENTAL RESULTS

The measured penetration depths, normalized by the length of the projectiles, are shown in Fig. 1.

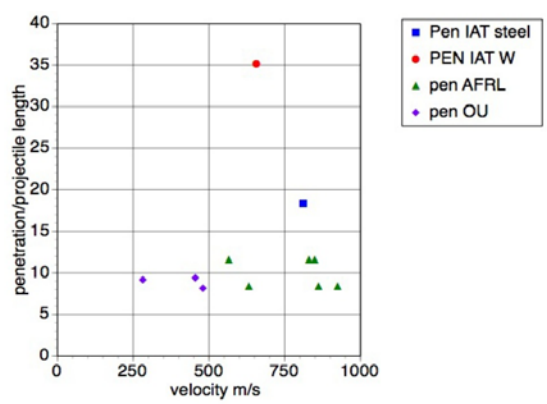

Figure 1. Normalized penetration vs. velocity.

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Penetration into soils is often described with a Poncelet equation:

$$M\frac{dV}{dt} = \rho CAV^2 + R\,. \qquad (1)$$

Here, M is the mass and V is the velocity of the projectile, C is essentially a drag coefficient, ρ is soil density, and R represents the soil strength. Coarse measurements using time-of-arrival detectors indicate that at high speeds deceleration appears to take place with constant drag, e.g., R is negligible [1,3,4]. But of course setting R equal to zero will never lead to a prediction of penetration depth, since the solution to equation (1) with $R = 0$ is

$$x = \frac{M}{\rho CA}\left[\ell n\left(\frac{V_0\rho CA}{M}\right)t\right], \qquad (2)$$

and as t goes to infinity, x goes to infinity. When the strength term is included, the solution is

$$x = \frac{1}{k}\ln\left[\frac{V_0^2 + \frac{R}{\rho C}}{u^2 + \frac{R}{\rho C}}\right], \qquad (3)$$

where $k = 2\rho C/\rho_p L$, ρ_p being the penetrator density. This equation gives the usual observation that penetration is proportional to penetrator length.

The data for M2 bullets provide an estimate of the Poncelet parameters. Four shots were conducted at nearly identical conditions: impact velocities of 320 to 360 m/s. In every case, there is an initial deceleration followed by a steady phase of almost constant deceleration. Examination of recovered bullets found the jacket intact but the core slipped forward relative to the jackets by about a millimeter. In many shots the PDV record bifurcates during the initial transient, strongly suggesting that both the core and jackets are being tracked, and the integration of velocity through the transient reproduces the observed core-jacket slip. Thus, the initial transient is interpreted as slippage of the jacket.

The recovered bullets showed patches of very fine, white sand. This material is without doubt the very fine sand powder that has been noted previously [1] in cavities where the penetration velocity exceeds 100 m/s, and noted in high-speed pictures by [5]. It was observed in [1] that the powdered sand grains are 1,000× smaller than the initial sand grains, and they may be comprised of quartz crystals.

Fitting Eq. (3) to the data in Fig. 2 (and from the other experiments) yields drag coefficients between 0.5 and 0.6. The influence of the strength term R cannot be resolved in the data. Drag coefficients about twice this high were measured for 5 mm diameter ogival rods hitting at 600 m/s and decelerating to about 100 m/s in [1]. The difference in drag coefficient measured here and previously may be due to a scale effect or to a variation of drag coefficient with velocity.

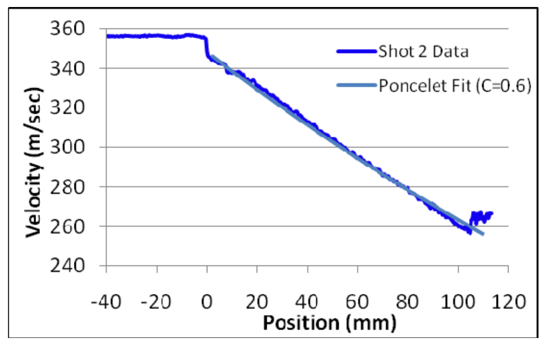

Figure 2. Deceleration of .50 M2 bullet in sand.

In their study of the dynamic properties of sand [6], Laine and Sandvik found that at low pressures the speed of sound in sand is equal to the speed of sound in air. Thus, these experiments with bullets are transonic. Deceleration was not significant over the distance that the measurements were made, so C = 0.5 to 0.6 corresponds to a bullet that is penetrating at just about the speed of sound, where the flow properties of sand may be quite sensitive to velocity.

Although final penetration should be proportional to length times a function of velocity, according to (3), that is clearly not the case in Fig. 1. Instead, at least for the OU and AFRL projectiles, normalized penetration was independent of velocity. Why this happened might be explained by an argument attributed to Sir Isaac Newton. Newton reputedly advised the Royal Navy that the way to make torpedoes penetrate deeper is not to shoot them faster, but to make them longer. His hypothesis was that the greater the kinetic energy of the torpedo, the greater the kinetic energy that must be imparted to the water to move it out of the way. This concept may be expressed mathematically by the equation

$$\frac{1}{2}\rho_p LAV^2 = \frac{1}{2}\rho_p \left\langle U^2 \right\rangle, \tag{4}$$

where P is penetration, and $<U^2>$ is the average value of the square of the penetration velocity. If we define κ as $<U^2> = V^2/\kappa$, so $P/L = \kappa\rho_p/\rho$, then we can compute κ for the data in Fig. 1. The result is Fig. 3. For the cylinder penetration data from AFRL and OU, κ is about two. It is greater, however, for the IAT data with high aspect ratio and smaller diameter. The normalized penetration was much greater in the IAT experiments. Thus, the scatter in Fig. 3 may arise because κ depends on penetration depth or on diameter. Another explanation is that Eglin sand may be stronger than Ottawa sand. For example, [7] points out that the strength of sand depends on grain shape.

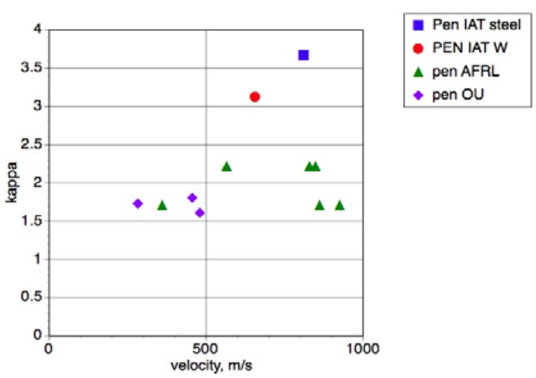

Figure 3. Ratio of the square of impact velocity to the average of the square of penetration velocity.

CONCLUSION

Final penetration depth in sand is weakly or not at all dependent on velocity. Initial deceleration in sand is well described by a drag model. It is noteworthy that the drag coefficient data and the kappa data can both be explained with the hypothesis that the resistance to penetration of sand depends on projectile diameter, being more for smaller scale projectiles.

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